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COMMENT ON PHOTONUCLEAR REACTIONS AT INTERMEDIATE ENERGIES

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Most of the recently published papers on photonuclear reactions at intermediate energies [1] either adopt or criticize the theoretical description by Hebach et al [2]. We implement here a simple and realistic calculation for the shell model knock-out contribution which considers a Woods-Saxon potential for the bound state and a shallower optical potential for the outgoing nucleon. Final states are explicitly orthogonalized to the initial state and the effects of the orthogonalization requirement are discussed.

The aim of this report is to dedicate some thought to the theoretical descriptions of photonuclear reactions at intermediate energies which have been developed over the last several years[1]. In particular, Hebach, Wortberg and Gari [2] studied photonuclear reactions with photon energies varying from 40 Mev to 140 Mev in considerable detail. In their approach they decomposed the cross section for single nucleon emission into different contributions, namely the shell model contribution, the two-body initial and final state correlations contribution and the exchange current (related to gauge invariance) contribution. Their results indicate that the exchange current contributions in (γ, p), (γ, n) and (γ, pn) reactions are the most important ones in the energy region above the giant resonance and below the pion threshold. Gari et al. criticised some model descriptions which do not ensure orthogonality between initial and final state wavefunctions and to tackle this problem, they enforced the single particle bound and scattering states to be

eigenstates of the same hamiltonian. It has been repeatedly argued [1] that the obtained cross sections can be severely miscalculated due to the use of such an unrealistically deep potential for the outgoing nucleon. In fact, it is well known that the scattered nucleon feels a much shallower potential than the one which adequately reproduces the relevant bound orbital and this is the physics which has to be taken into account in this context. The wavefunctions considered by Hebach et al [2] are known not to be the adequate scattering wavefunctions for the situation in hand.

In this work we concentrate just on the so-called shell model contribution and investigate its sensitivity to changes in scattering wavefunctions including orthogonality requirements. The problem of orthogonality between initial and final states for direct nucleon knock-out reactions at intermediate energies has also been discussed by Boffi et al. [3]. They compared the cross sections calculated with the wavefunction orthogonalized via the Gram- Schmidt method with the cross sections calculated with the optical potential wavefunction. Here the orthogonalization is performed by solving a projected inhomogeneous Schrödinger equation in an optical model continuum designed so as to reproduce the nucleon elastic scattering at the relevant energies.

Except for exchange current effects, which we do not consider here, the absorption of a photon leading to subsequent disintegration through an open channel f (e.g. nuclear emission) is formally described by an amplitude which can be written as

$$T_{\gamma f} = < \psi_f^{(-)} \mid \sum_i O_{\vec{k},\vec{\epsilon}}(\vec{r}_i) \mid \psi_0 >, \qquad (1)$$

where the one-body operator $O_{\vec{k},\vec{\epsilon}}(\vec{r})$ is associated to the perturbative absorption of a photon of momentum $\vec{k}$ and polarization $\vec{\epsilon}$ by a nucleon at $\vec{r}$ (spin variables are implicitly

included in this symbol). The target ground state $\mid \psi_0 >$ and the final state $\mid \psi_f^{(-)} >$ satisfy the Schrödinger equations

$$H \mid \psi_o >= 0 \quad ; \quad [E - H] \mid \psi_f^{(-)} >= 0. \tag{2}$$

Since the target state energy has been set to zero, one has $E = \hbar kc$. The full Hamiltonian of the nuclear system is H and the final state contains asymptotically free (or Coulomb) waves in channel f and incoming waves in all open channels. Obviously $< \psi_0 | \psi_f^{(-)} >= 0$ here.

Useful reduction of $T_{\gamma f}$ in order to expose a variety of competing reaction mechanisms can be achieved by treating the equation satisfied by the final state in the framework of a comprehensive reaction theory. We adopt here a formulation based on the so called optical background representation of Kawai, Kerman and McVoy [4]. Since the initial and final (many-body) states are orthogonal, it is convenient to analyse the latter in terms of an operator P projecting onto the observed channel f and a complementary projector Q so that

$$P + Q = 1\!\!1 - \mid \psi_0 >< \psi_0 \mid = R \tag{3}$$

in addition to the usual relation $PQ = QP = 0$ and the standard idempotency and hermiticity conditions on P and Q. Eq.(3) in fact implies the splitting of the nuclear phase space in three sectors, containing respectively the target state, the observed channel (constructed so that $P|\psi_0 >= 0$) and "everything else". With the help of (3) we next write

$$\mid \psi_f^{(-)} >= P \mid \psi_f^{(-)} > + Q \mid \psi_f^{(-)} > \tag{4}$$

and find in the usual way that $P \mid \psi_f^{(-)} >$ satisfies

$$[E - H_{opt}^{\dagger}] P \mid \psi_f^{(-)} >= V_{PQ} \frac{1}{E - i\eta - H_{QQ}} V_{QP} P \mid \psi_f^{(-)} > \tag{5}$$

where

$$H_{opt}^{\dagger} = H_{PP} + H_{PQ} \frac{1}{E - iI - H_{QQ}} H_{QP} \tag{6}$$

is the optical Hamiltonian for channel f corresponding to an energy averaging interval of width I and

$$V_{PQ} = H_{PQ} \sqrt{\frac{-iI}{E - iI - H_{QQ}}} \quad ; \quad V_{QP} = \sqrt{\frac{-iI}{E - iI - H_{QQ}}} H_{QP} \tag{7}$$

so that the right hand side of eq. (5) gives rise to fluctuation contributions with vanishing energy average. A formal solution to this equation can be obtained as

$$P \mid \psi_f^{(-)} >= \mid \chi_f^{(-)} > + fluctuation\ term \tag{8}$$

where $\mid \chi_f^{(-)} >$ is an eigenfunction of the optical Hamiltonian. For the purpose of the present discussion we ignore contributions to $T_{\gamma f}$ arising from the fluctuation term and from $Q \mid \psi_f^{(-)} >$. They involve either compound nucleus effects or various correlation effects in the final state in an essential way. We focus instead on the simplest "direct" contribution

$$T_{\gamma f}^{dir} =< \chi_f^{(-)} \mid \sum_i O_{\vec{k},\epsilon}(\vec{r}_i) \mid \psi_0 > \tag{9}$$

to the photodisintegration amplitude and illustrate its evaluation in the framework of a simple model for the $^{16}O(\gamma, p_0)$ process.

This model consists in adopting extreme independent particle ansatze for the target state $\mid \psi_0 >$ and for the residual nucleus state in $|\chi_f^{(-)} >$. In this way eq.(9) reduces effectively to a single nucleon transition from the appropriate bound orbital of $\mid \psi_0 >$ to an

(orthogonal) optical model scattering state. The optical model potential is determined phenomenologically and the orthogonality requirement stemming from (3) is implemented by restricting the optical model continuum to the subspace orthogonal to the bound nucleon orbital in $\mid \psi_0 >$. This procedure has been used previously in reaction theory calculations [5] notably for analysing isobaric analog resonances [6], where a similar orthogonality requirement must be imposed. It is implemented in the computer subroutine TABOO [7], which we use in the calculations described below.

As stated earlier we consider the reaction $^{16}O(\gamma,p)^{15}N$ and calculate its shell model angular distributions for photon energies equal to 61.9 Mev and 82 Mev.

Three different situations are considered. The first one reproduces the calculation of Gari et al. [2] (figures 6 and 7 of their paper, respectively for $E_\gamma = 61.9$ Mev and $E_\gamma = 82$ Mev), where the initial bound and final scattering states are orthogonal eigenstates of the same potential well. The Woods-Saxon potential parameters are $U_0 = 58.5 Mev$; $R_0 = 2.77 fm$; $a = 0.5 fm$ and no spin-orbit potential is included so that there is no j-dependence in the knock-out amplitude. Secondly, we consider different potentials for the bound states and for the outgoing scattered nucleon. The same potential (mentioned above) is taken for the bound state wavefunction. To calculate the wavefunctions of the outgoing nucleon we use the optical potential of Menet et al [8]. Menet's potential adapted to the present case gives the parameters shown in table I, where W and W_D are respectively the imaginary volume and surface potential strengths and V_{SO} is the spin-orbit potential. In this case, one should bear in mind that the bound state wavefunctions and the scattered particle wavefunctions are not orthogonal since the scattered proton sees a much shallower potential than the one seen by the bound state. However, the resulting wavefunctions

presumably give a better picture of the dynamics involving the ejected nucleon. The third part of our calculation uses the same potential parameters as the second but the continuum wavefunctions in the partial waves corresponding to the initial bound state are orthogonalized to the latter.

In figures 1 and 2 we show the resulting cross sections for the three situations described above respectively for $E_\gamma = 61.9$ Mev and $E_\gamma = 82$ Mev.

Multipoles up to L=4 have been taken into account and all contributing partial waves included. The solid line represents the results obtained by means of the method used in ref. [2]. The dotted line represents the cross section calculated with different potentials for the initial and final non-orthogonal states and the dashed line represents the cross section calculated with the orthogonalized states.

One can notice that there are almost no differences between the second and third calculations. This is easily understood from the fact that the orthogonality requirement actually represents a minor distortion of the scattering wavefunction in the relevant partial waves since the dangerous overlap is rather small anyway in the present regime. The wavefunction obtained from the Schrödinger equation with the optical potential is indeed very similar to the orthogonalized one while both of them are sensibly different from the scattering wavefunction in the deep well. Hence, we emphasize that ensuring orthogonality by diagonalizing a hamiltonian containing a very deep potential is a dangerous and unrealistic way of taking the ortogonality between the initial and final states into account.

A similar conclusion was reached in ref. [3], where the authors claim that the effect of orthogonality is very small in (γ,p) reactions.

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Figure Captions

Figure 1 - $^{16}O(\gamma,p)$ angular distribution for $E_\gamma = 61.9$ Mev. The solid line shows the calculation for orthogonal initial and final states which are eigenstates of the same hamiltonian containing the same potential. The dotted line shows the calculation for non-orthogonal initial and final states obeying respectively a Woods-Saxon potential and a realistic final state potential. The dashed line shows orthogonal initial and final states obeying the above mentioned potentials. The experimental data are taken from ref [2].

Figure 2 - The same as in figure 1 but for $E_\gamma = 82$ Mev.

Table Caption

Table I - Values used for the parameters of the optical potential by Menet et al [4] when E_γ is respectively 61.9 and 82 Mev.

TABLE I

	$E_\gamma = 61.9$ Mev	$E_\gamma = 82$ Mev
V_0	37.55	33.13
r_0	1.16	1.16
a_0	0.75	0.75
W	6.77	8.58
W_D	1.11	0.1
r_W	1.37	1.37
r_D	1.37	1.37
a_W	0.5	0.5
a_D	0.5	0.5
V_{SO}	6.04	6.04
r_{SO}	1.064	1.064
a_{SO}	0.78	0.78

Figure 1

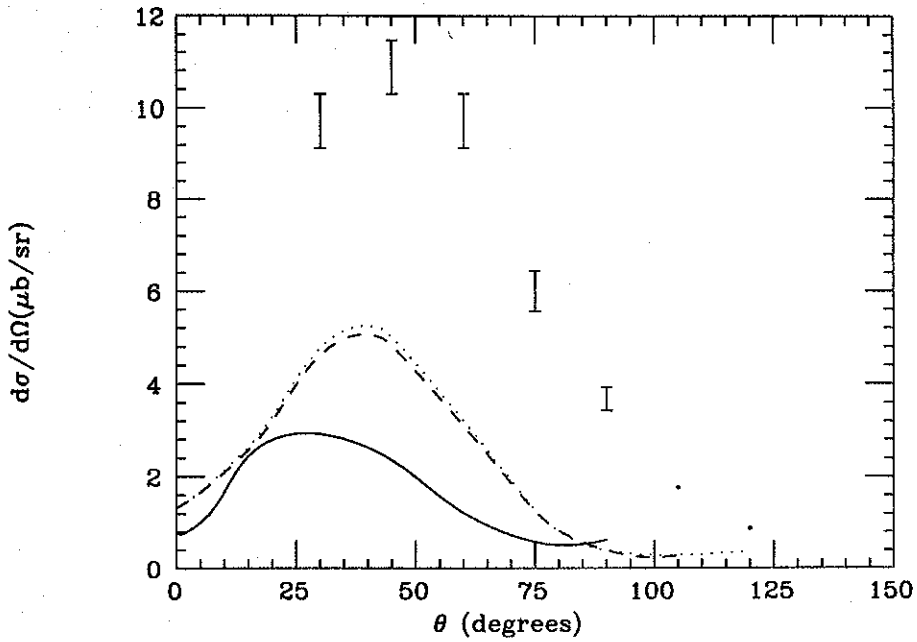

Figure 2